
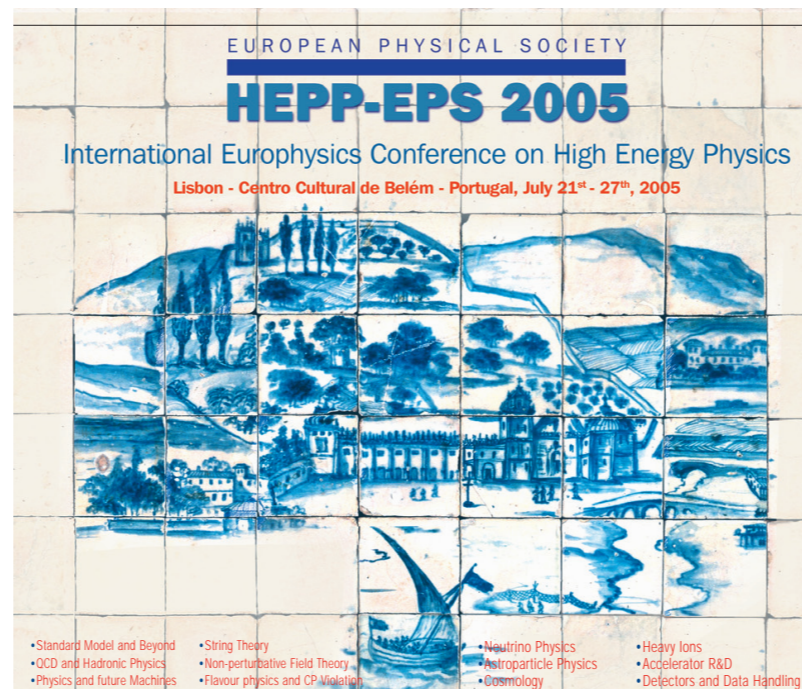


A PHENIX Perspective on Soft Observables

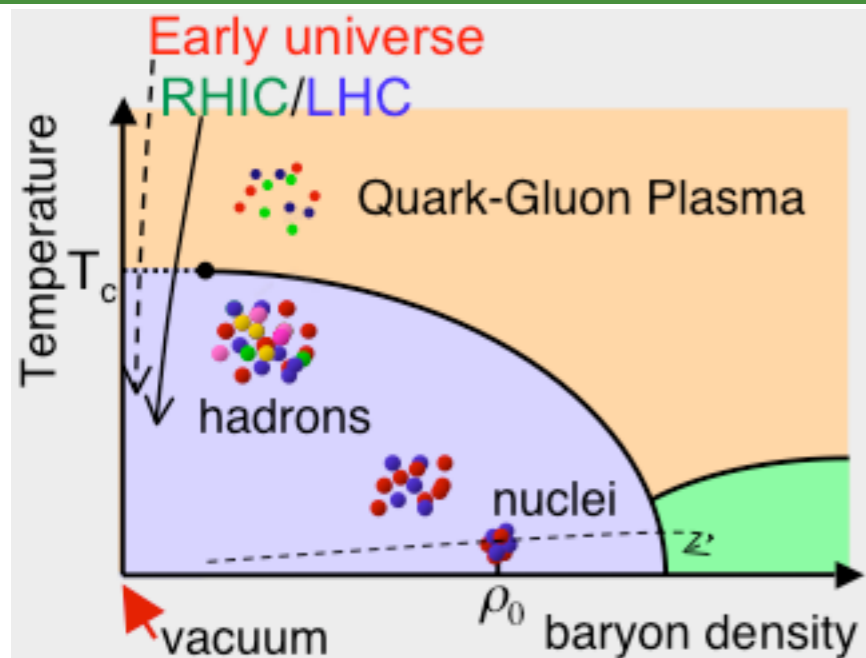
Jason Newby for the PHENIX Collaboration
Lawrence Livermore National Laboratory 



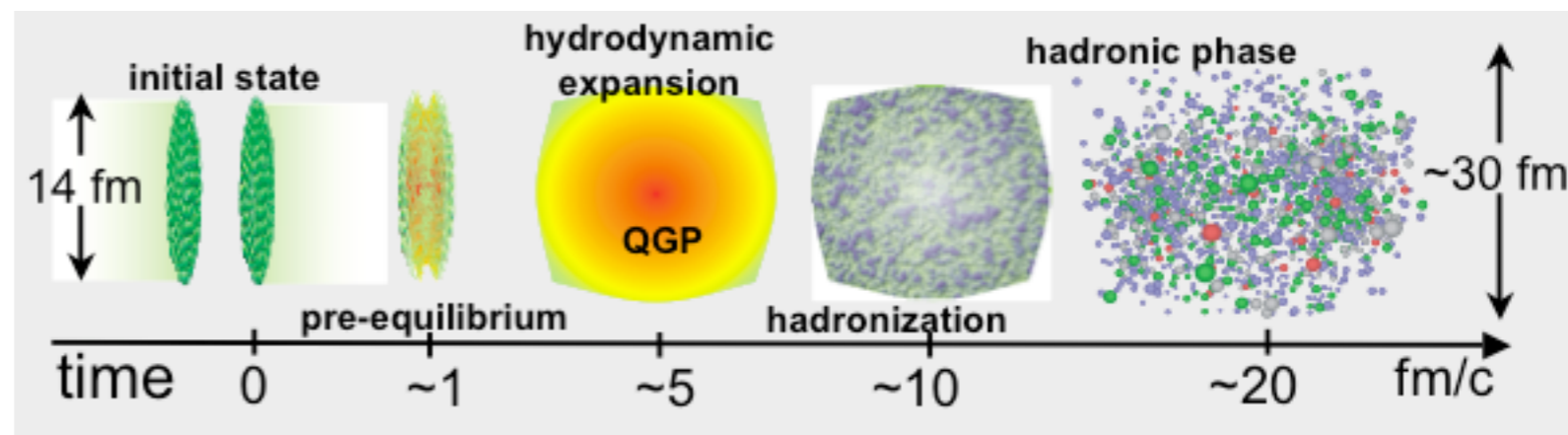
UCRL-PRES-214167

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48

Heavy Ion Collisions



Time Evolution



QCD beyond normal nuclear temperature & density

Are we creating a thermalized medium?

- Is medium sufficiently hot and dense?
- Does the medium exhibit collective behavior?

Are we creating a new Phase?

- Do we observe critical behavior?
- Space-Time evolution?

Explore the properties of the medium!

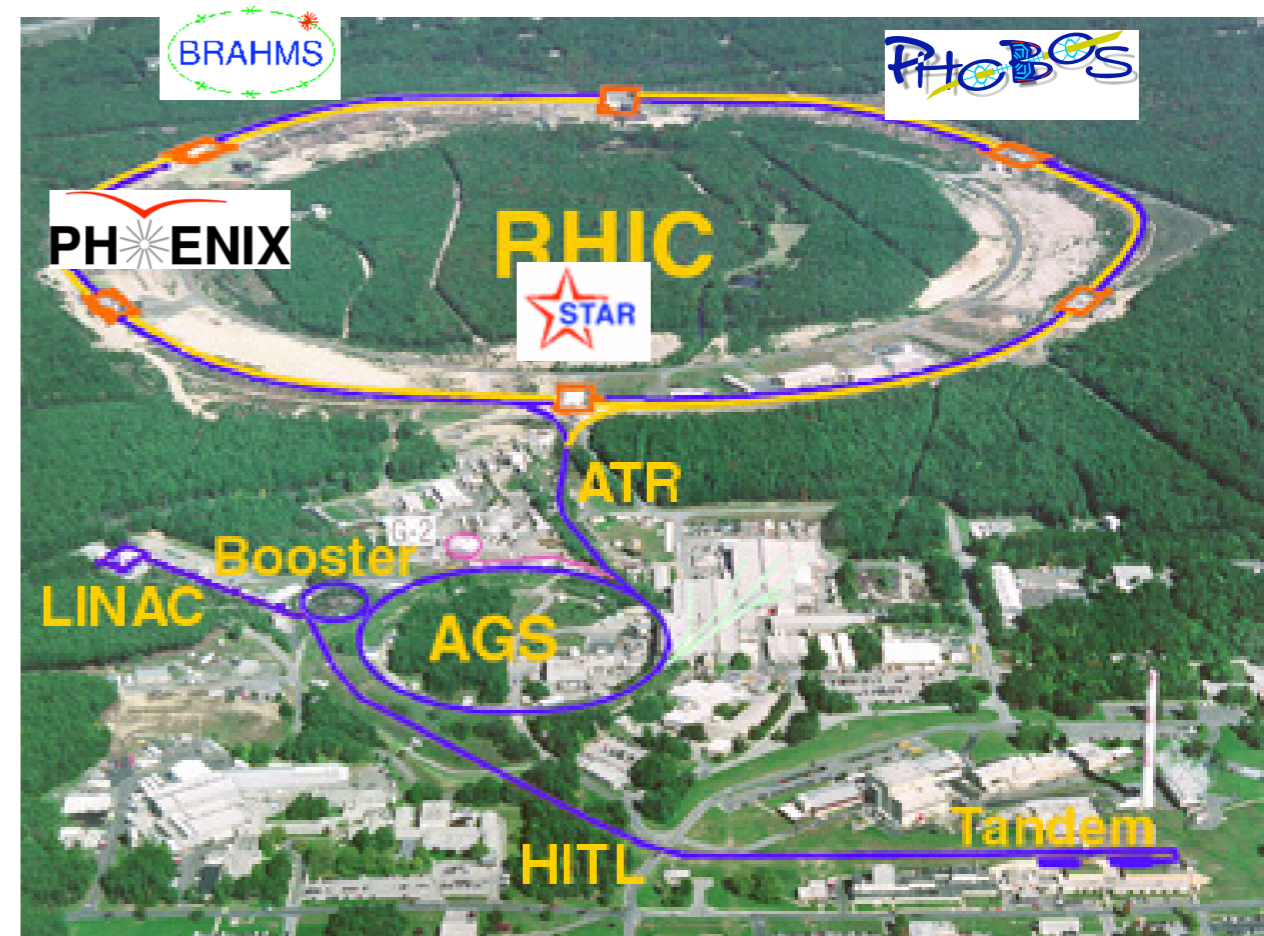
- Temperature
- Parton Number Density
- Energy Density
- Opacity
- Viscosity
- Pressure
- Thermalization Time & Extent
- Deconfinement
- Degrees of Freedom
- Recombination to Final State
- Equation of State
- Color Thermal Transport Properties
- Space-Time Evolution

Experimental Observables

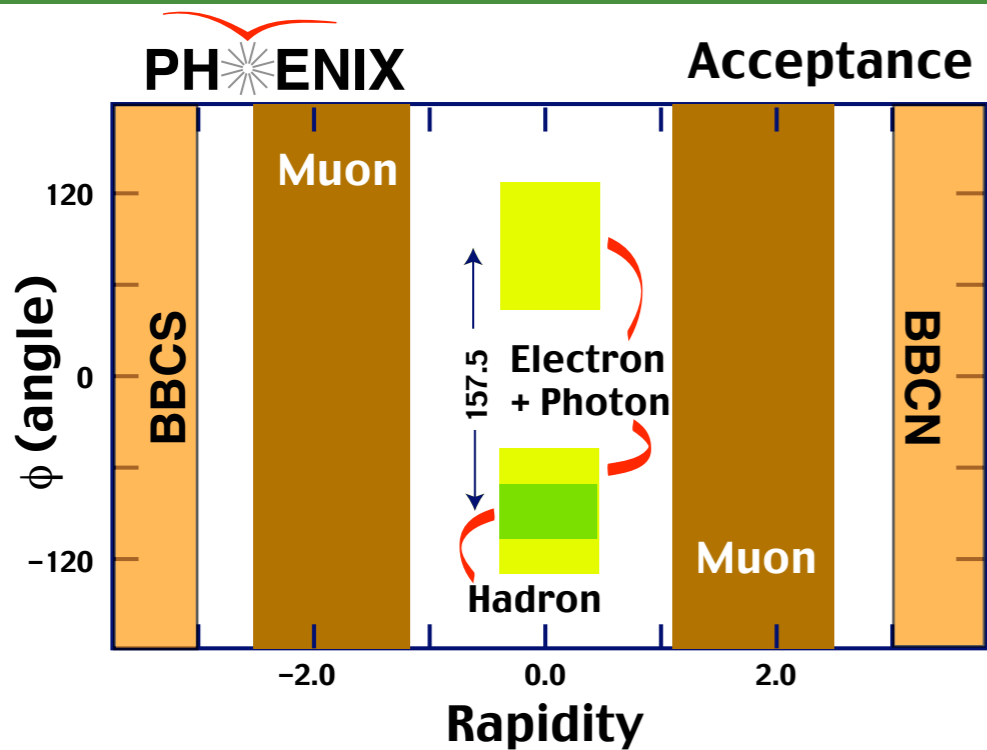
Trends:
System Size: p+p A+A p+A
Collision Energy

Run	Species	Energy	Events
1	Au+Au	130	10M
2	Au+Au p+p	200 200	170M 3.7G
3	d+Au p+p	200 200	5.5G 6.6G
4	Au+Au	200 62	1.6G 58M
5	Cu+Cu p+p	200 62 22.5 200	8.6G 0.4G 9M 85G

- Multiplicity
- Transverse Energy
- Identified Spectra
- Particle Ratios
- Fluctuations
- Elliptic Flow
- Bose-Einstein Correlations
- Hard Probes
 - See presentation by D Peressounko



PHENIX Experiment

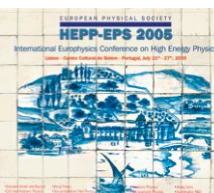
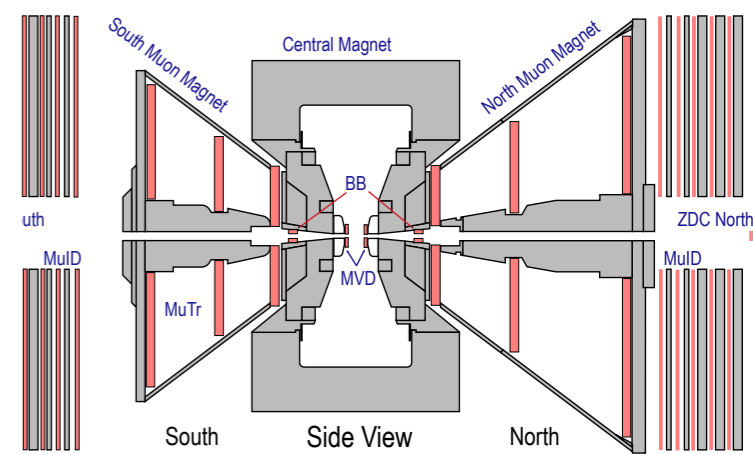
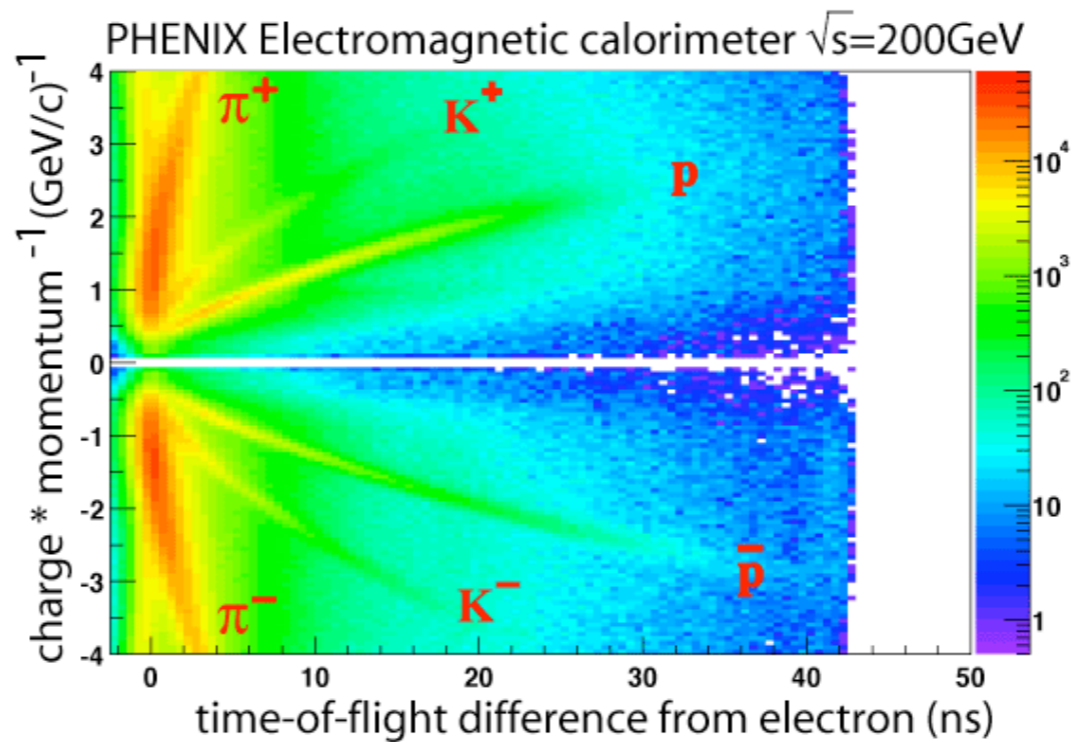
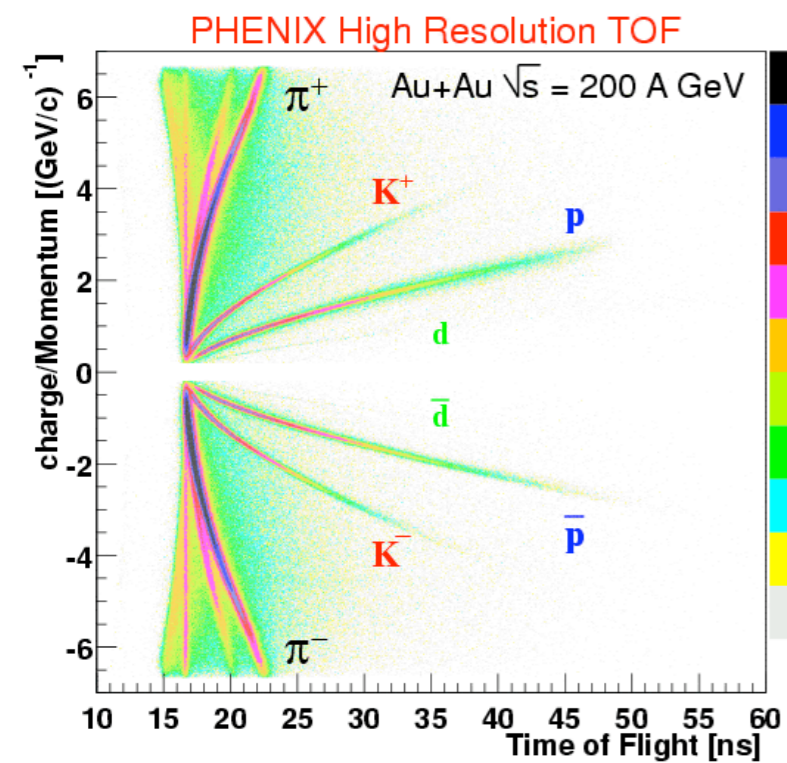
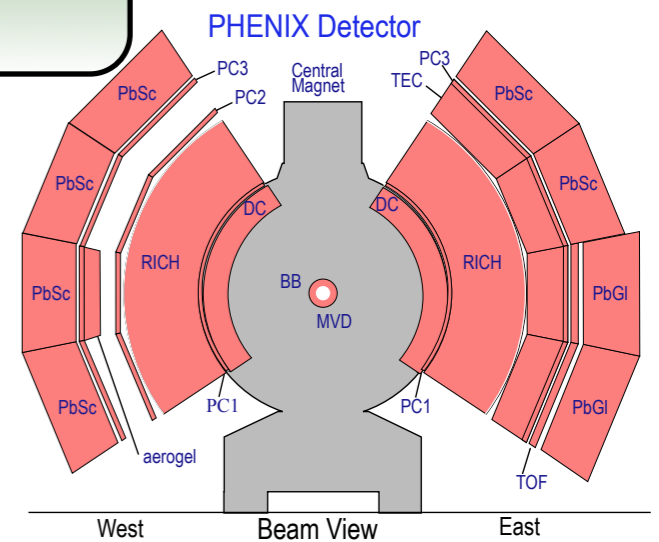


Identified

$$\pi^{\pm}, K^{\pm}, p, \bar{p}, d, \bar{d}, e^{\pm}, \mu^{\pm}$$

Reconstructed

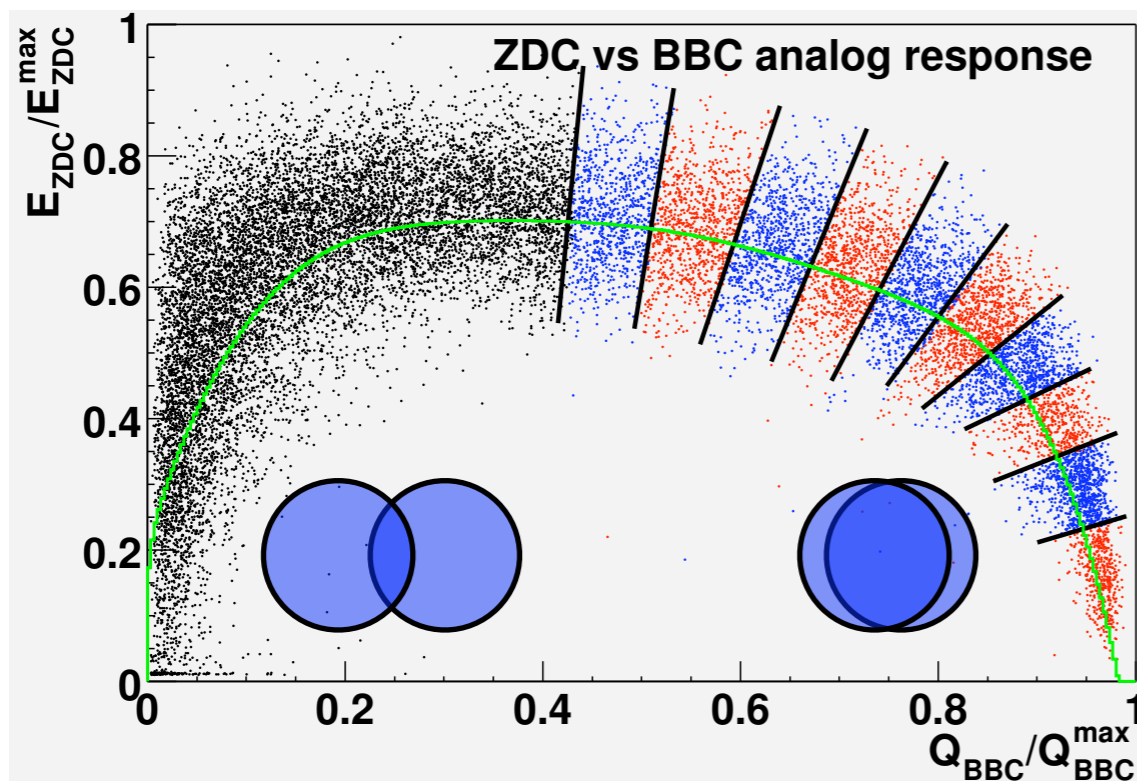
$$\pi^0, \Lambda, \Phi, J/\psi$$



Event Characterization

Centrality

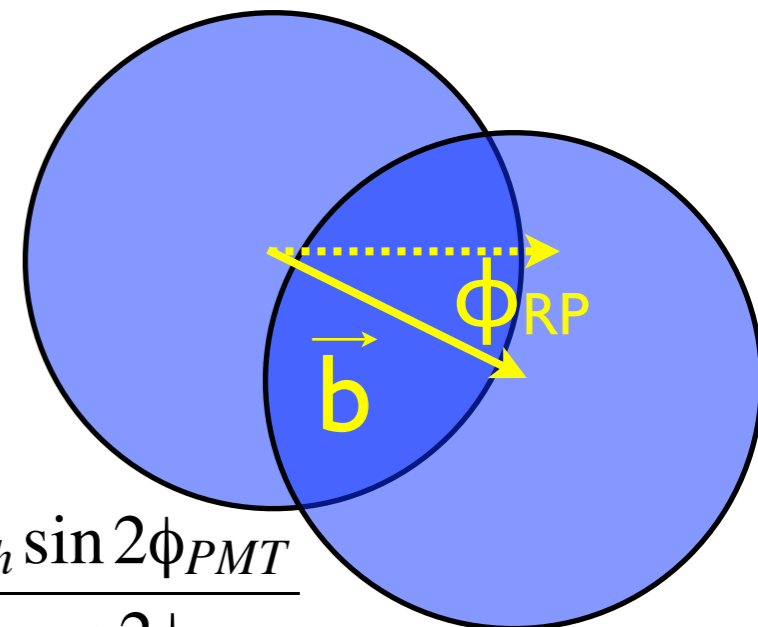
Unbound Spectator Neutrons



$N_{ch} (3 < \eta < 4)$

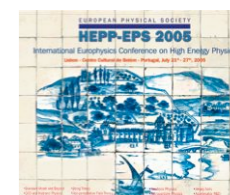
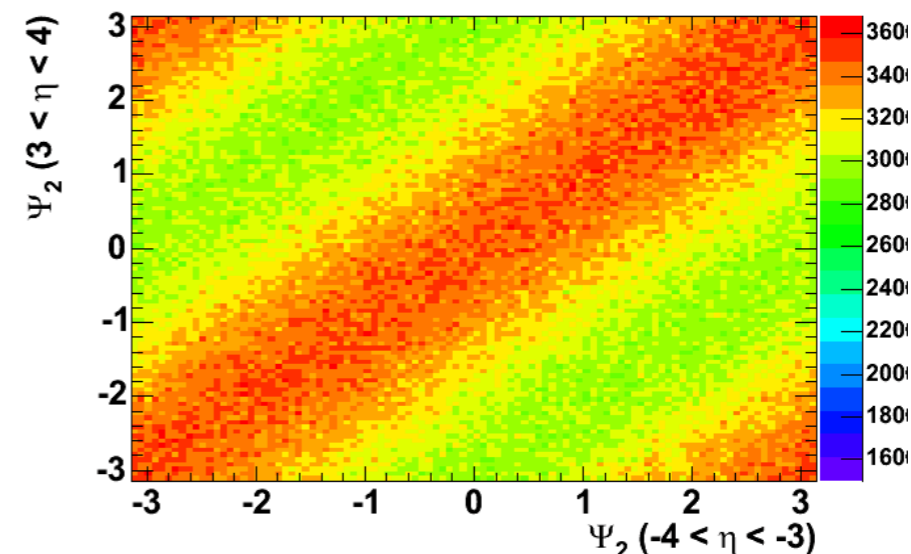
Participating Nucleons, N_{part}
Binary N-N Collisions, N_{coll}

Reaction Plane

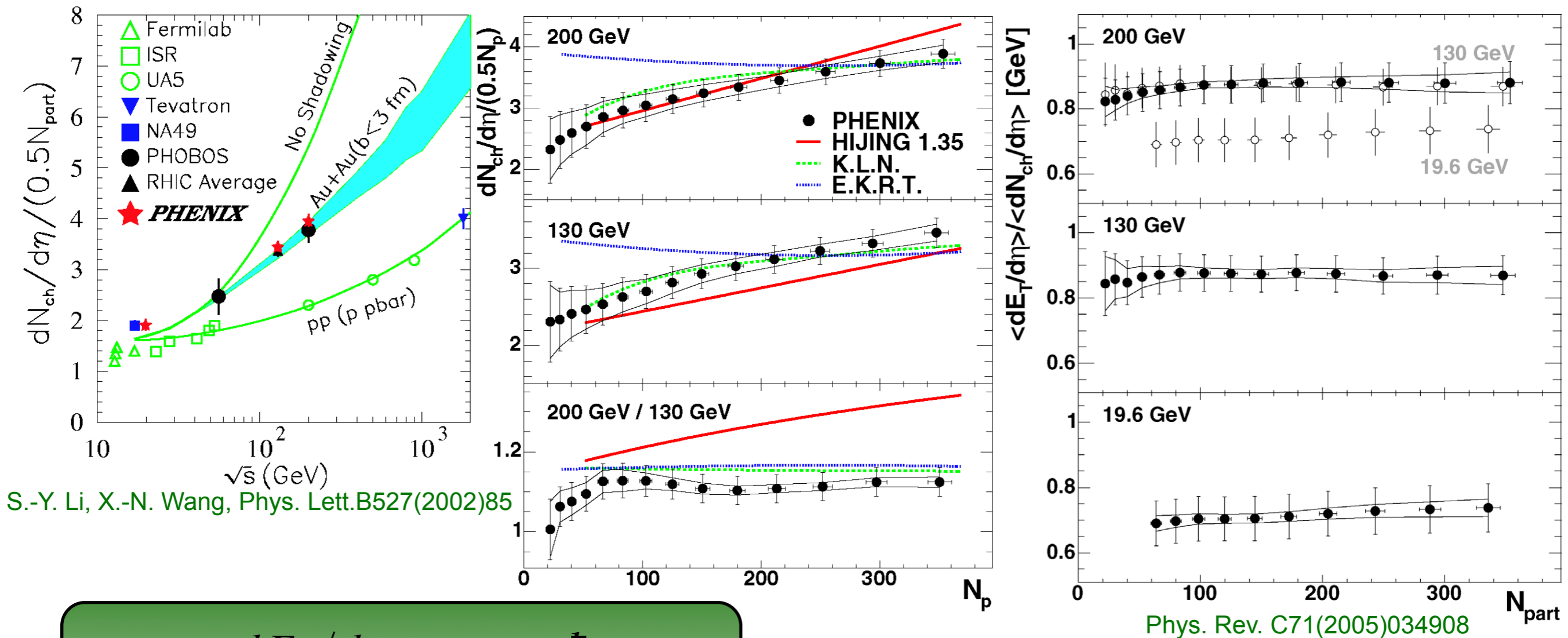


$$\tan 2\Phi_{RP} = \frac{\sum n_{ch} \sin 2\phi_{PMT}}{\sum n_{ch} \cos 2\phi_{PMT}}$$

BBC SOUTH 2nd vs BBC NORTH 2nd

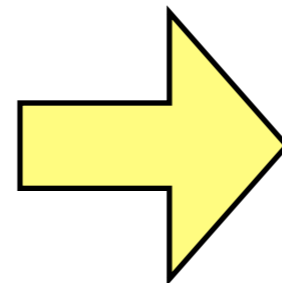


Energy Density: N_{ch} & E_T



$$\langle m_T \rangle \simeq \frac{dE_T/d\eta}{dN/d\eta} \quad t = \frac{\hbar}{m_T}$$

$$\langle \epsilon(\tau_{formation}) \rangle = \frac{1}{\tau_{formation} A} \frac{dE_T(\tau_{formation})}{dy}$$



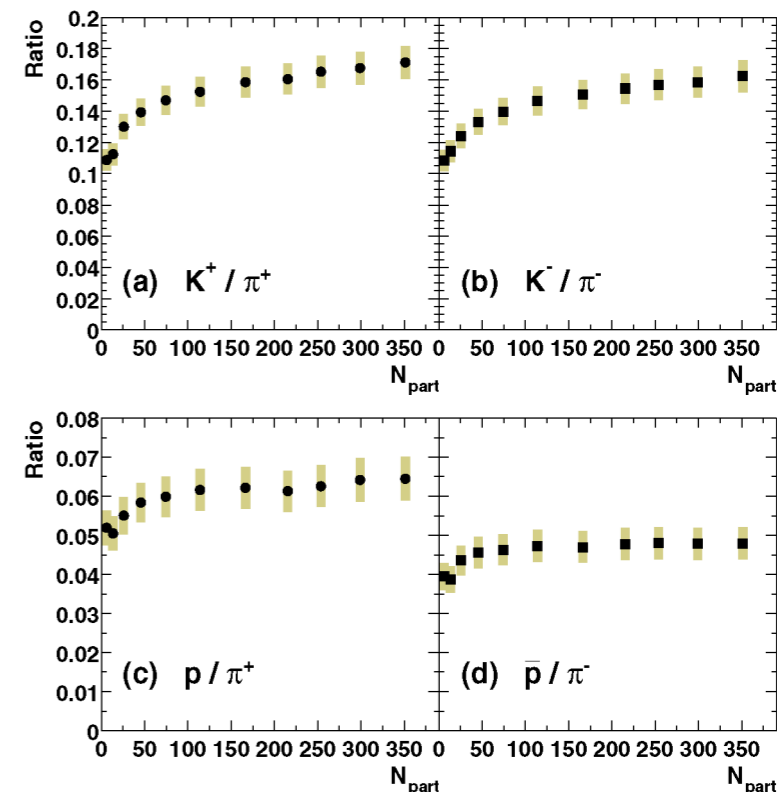
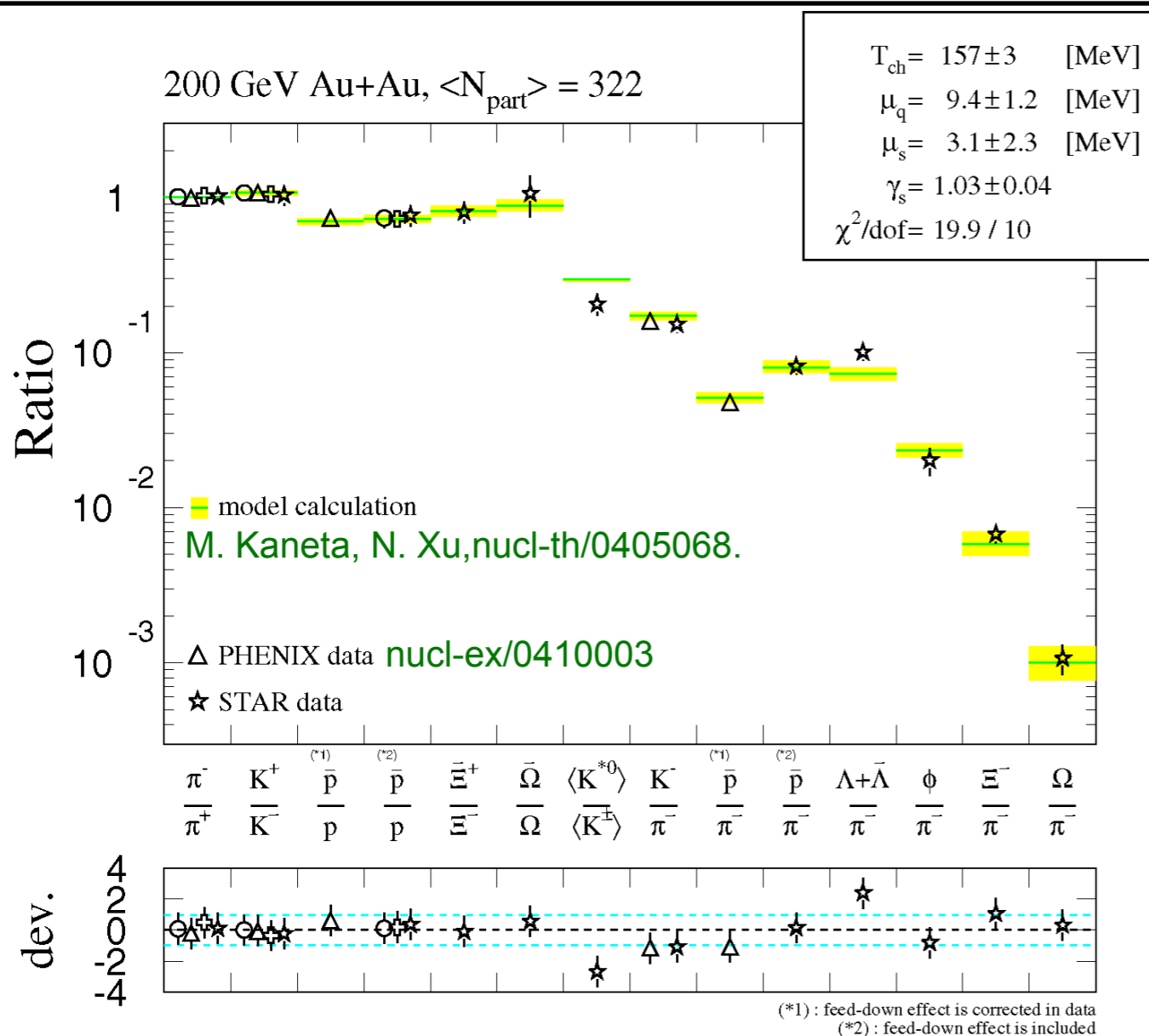
Peak Energy Density
+15 GeV/fm³

Nucl.Phys. A757 (2005) 184-283



Chemical Equilibrium

Increased System size reduces constraints on locally conserved quantities.



Phys. Rev. C69(2004)034909

Thermal Model¹

$$T_{\text{chem}} = 157 \pm 3 \text{ MeV}$$

$$\mu_B = 23 \pm 3 \text{ MeV}$$

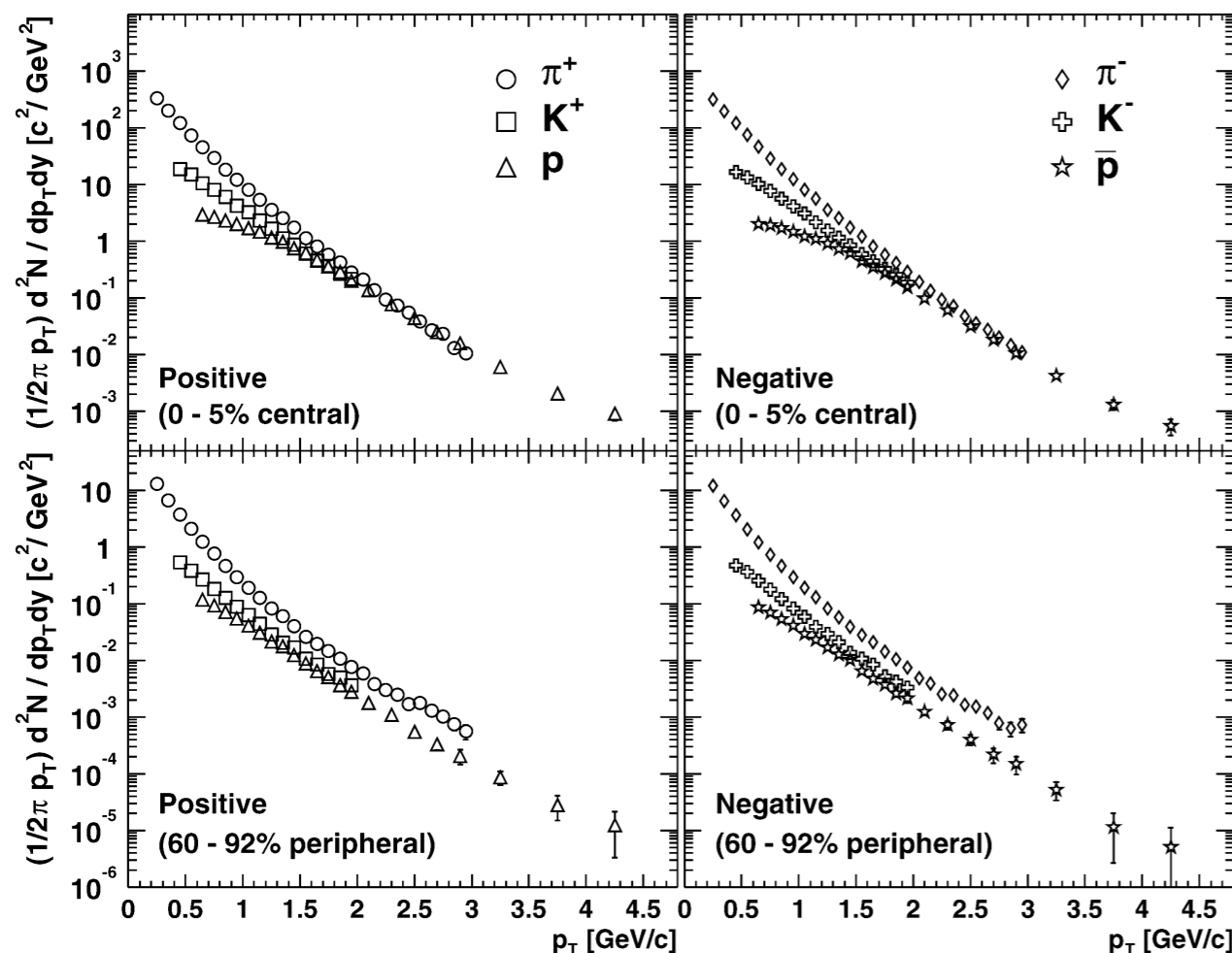
$$\gamma_s = 1.03 \pm 0.04$$

¹Kaneta and Xu

Strangeness fully saturated.

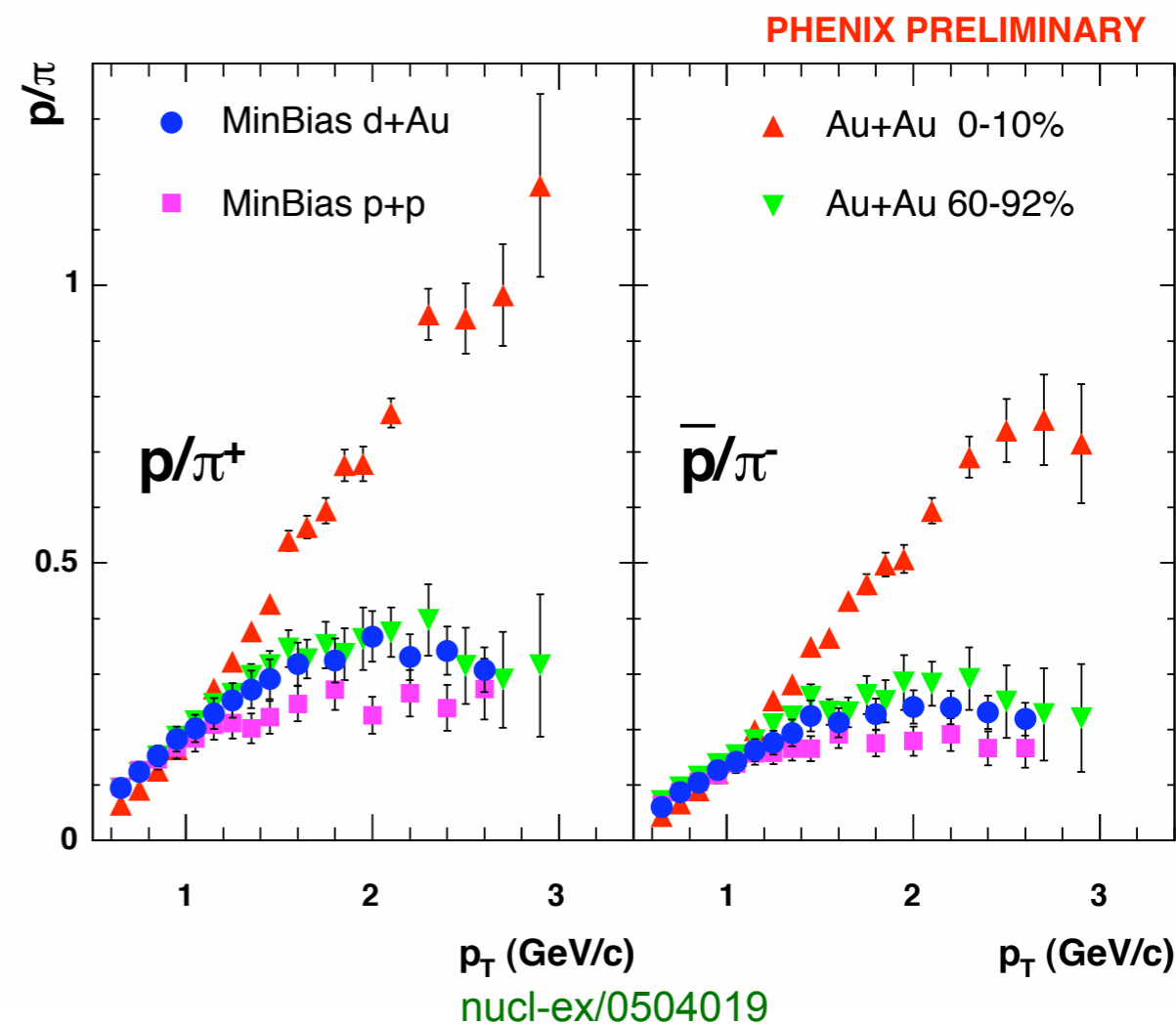
Spectra

- Pion contribution from decays at low p_T
- Kaons exponential over measured range
- Protons comparable to π 's above 2 GeV/c



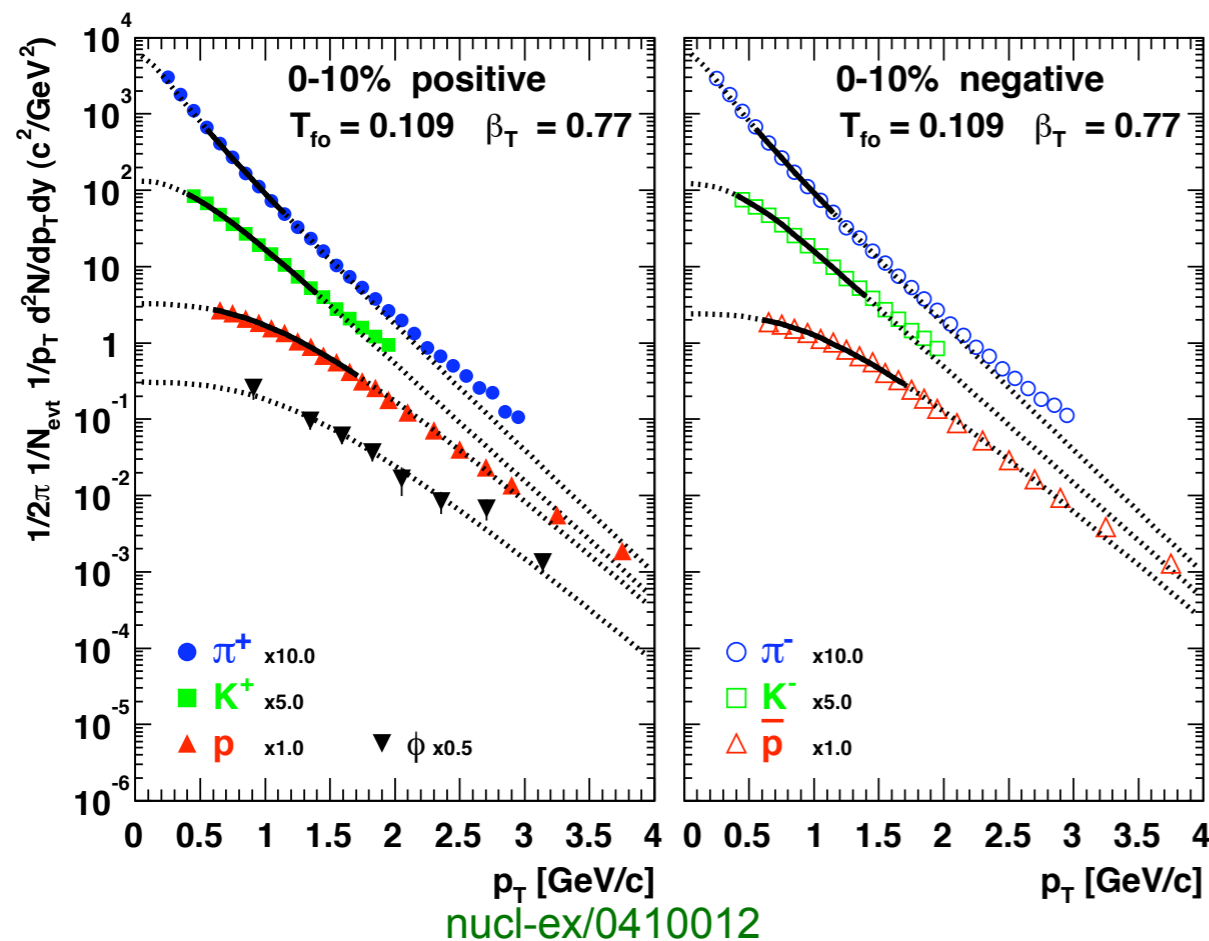
Phys. Rev. C69(2004)034909

$$\langle \beta_T \rangle \sim 0.5$$



Proton excess at mid- p_T not observed in p+p, d+Au

Radial Flow

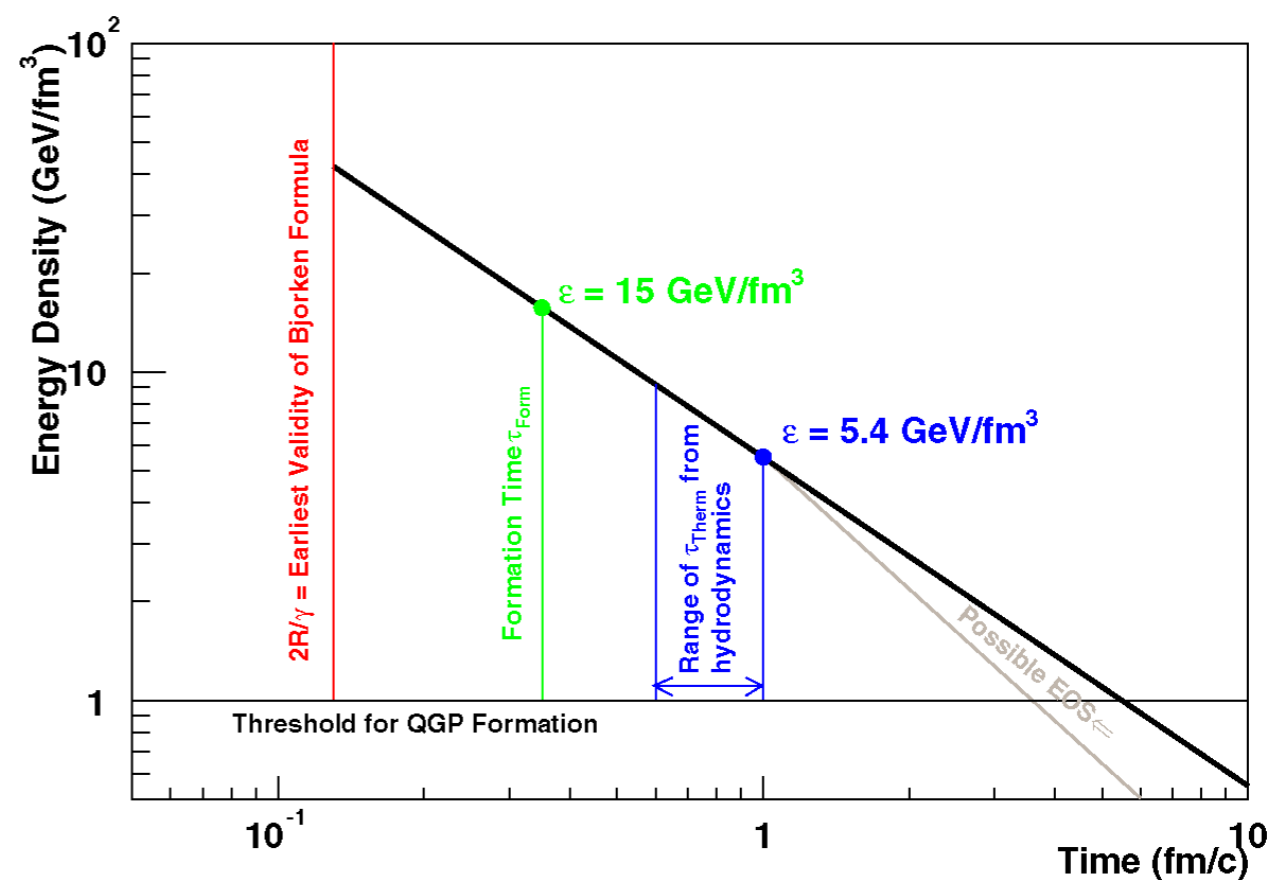


Hydrodynamic Fit

$$T_{fo} = 109 \text{ MeV}$$

$$\beta_T = 0.77$$

Time Evolution of Energy Density in the Bjorken Picture

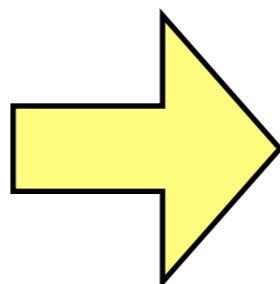


Nucl.Phys. A757 (2005) 184-283

Elliptic Flow

Spatial Anisotropy

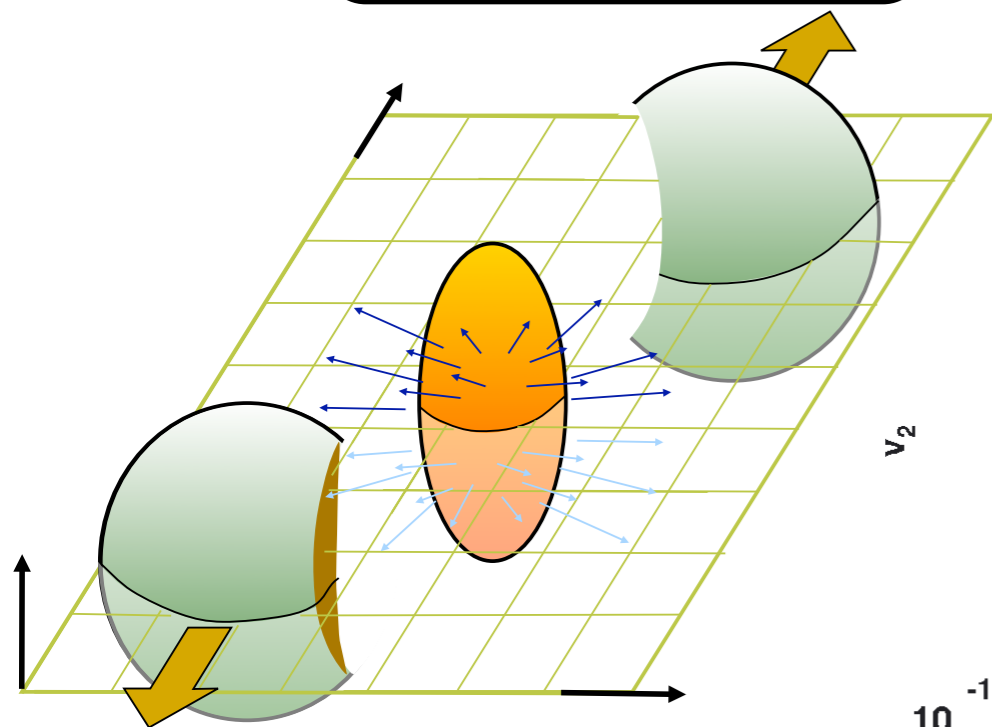
$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$



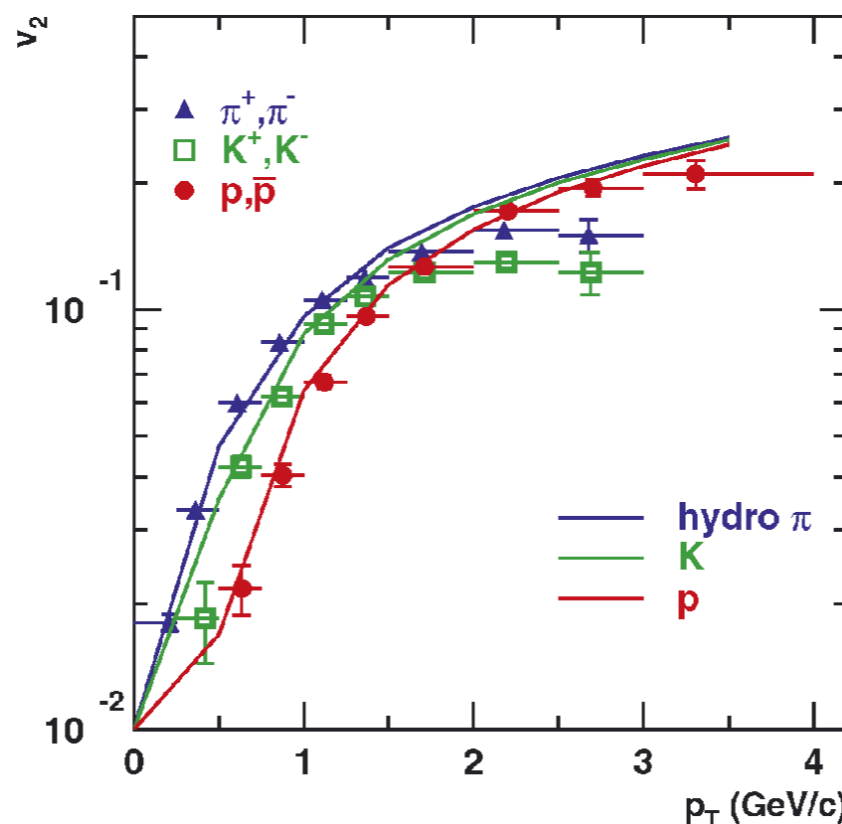
Momentum Anisotropy

$$\frac{d^2N}{d\phi dp_T} = N_0 (1 + 2v_2(p_T) \cos(2\phi))$$

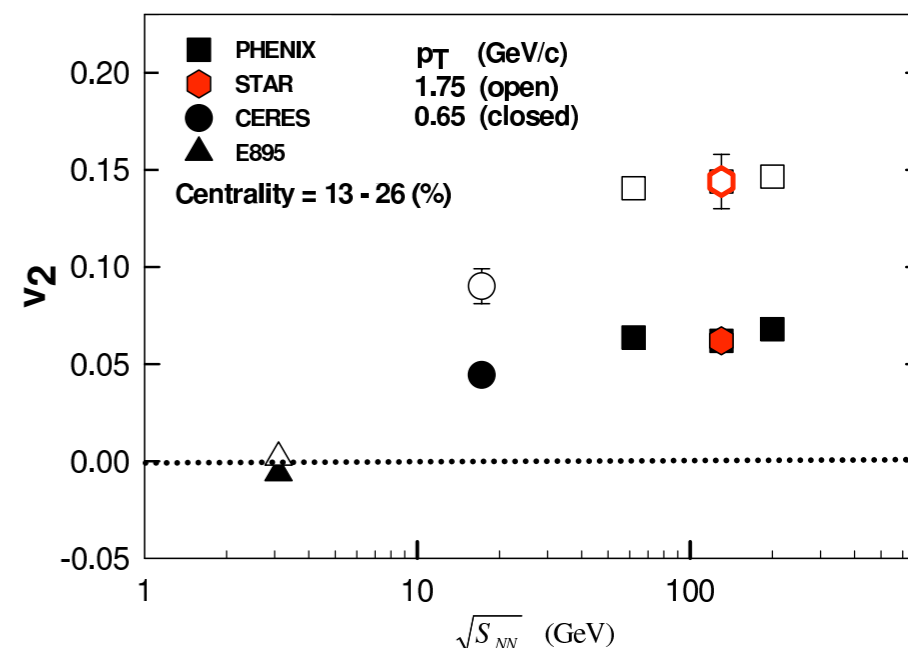
Elliptic Flow Saturated



Phys. Rev. Lett. 91(2003)182301

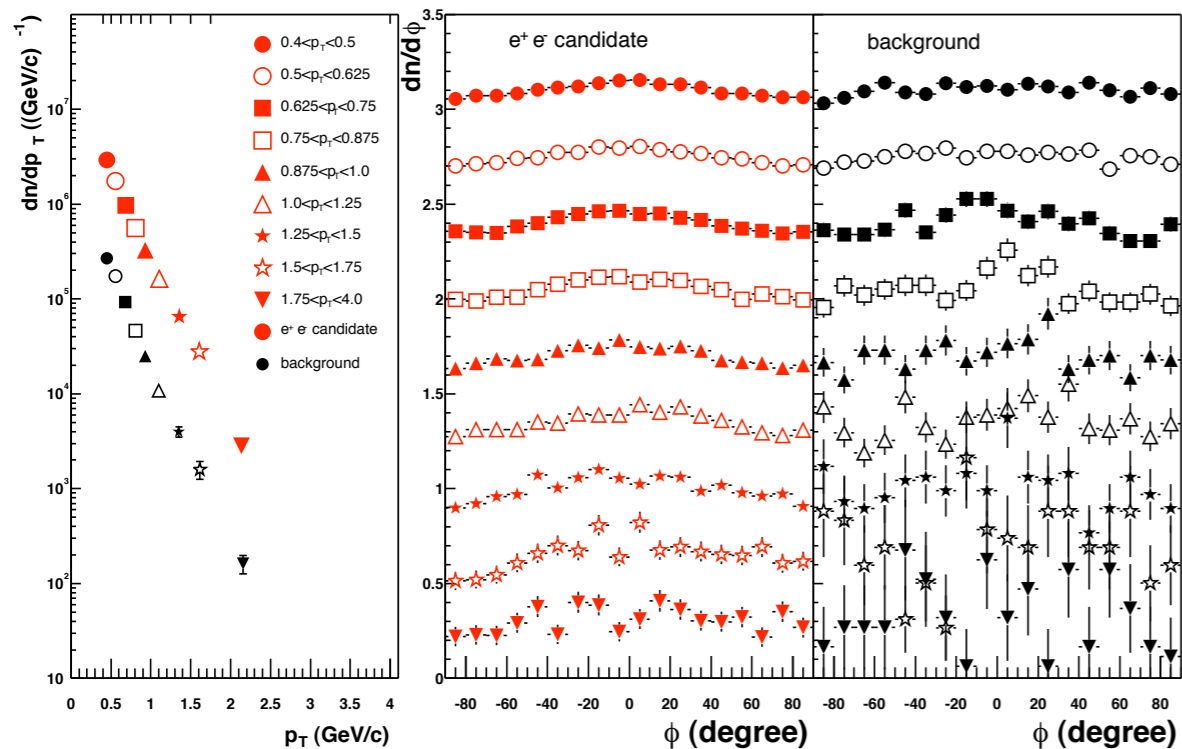


P. Huovinen et al., Phys. Lett. B503(2001)58



Phys. Rev. Lett. 94, 232302

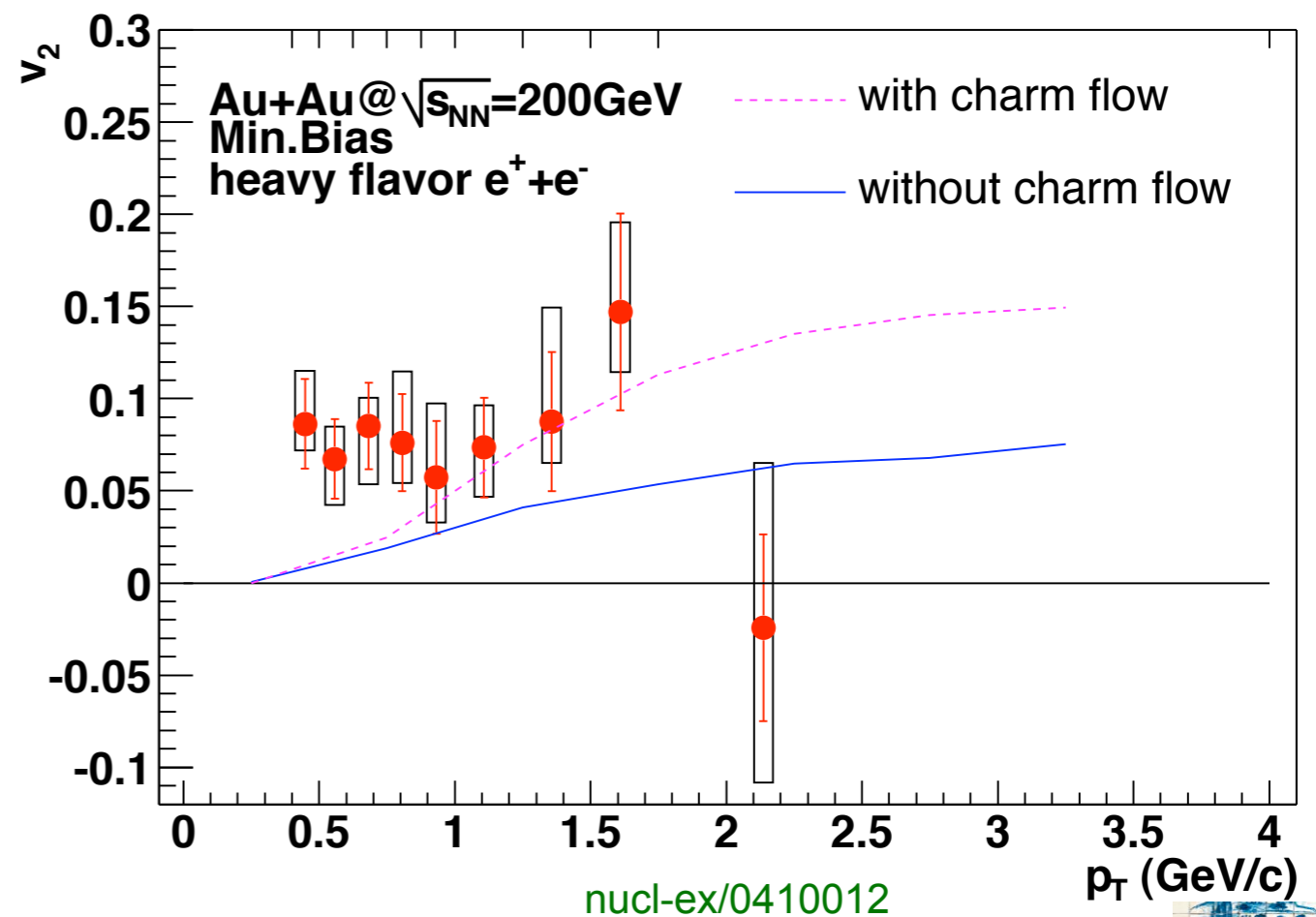
Elliptic Flow - Heavy Flavor



nucl-ex/0410012

Charm flow may indicate thermalization of charm.

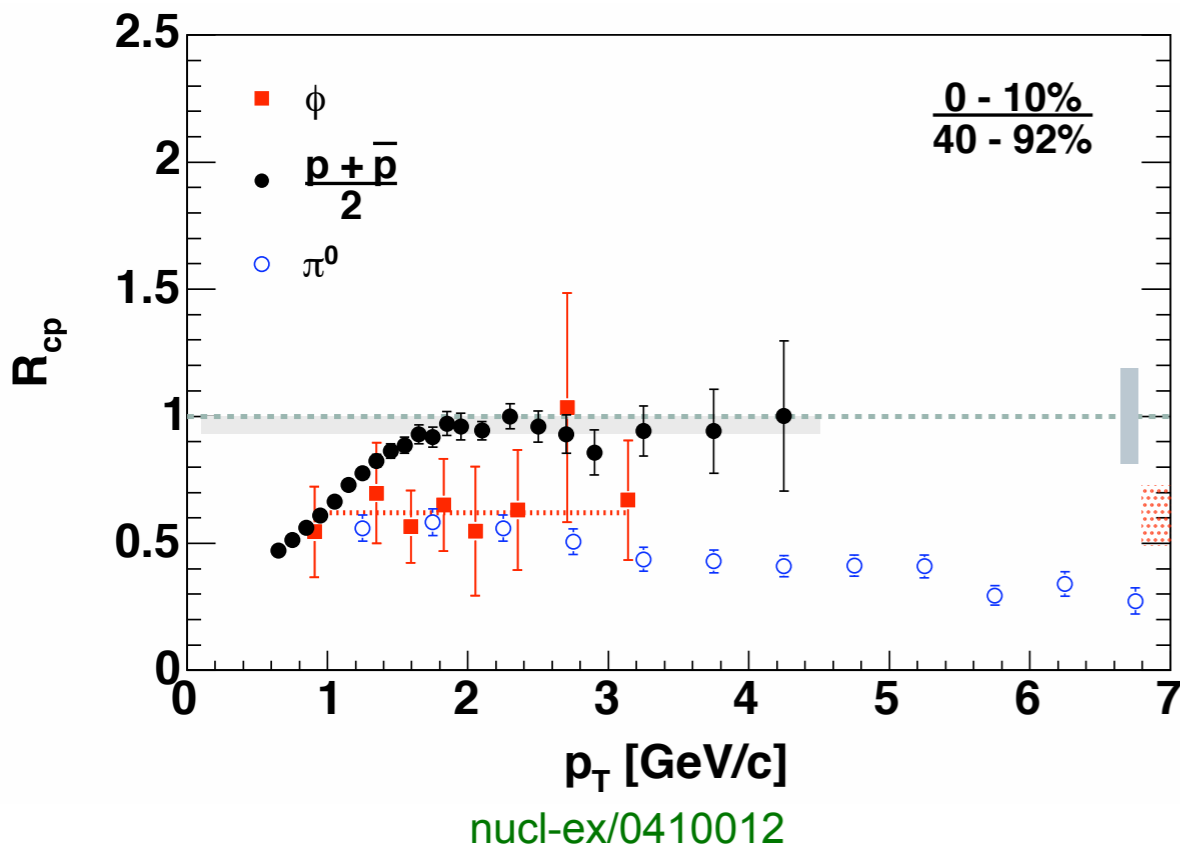
Charm extracted from electron spectra



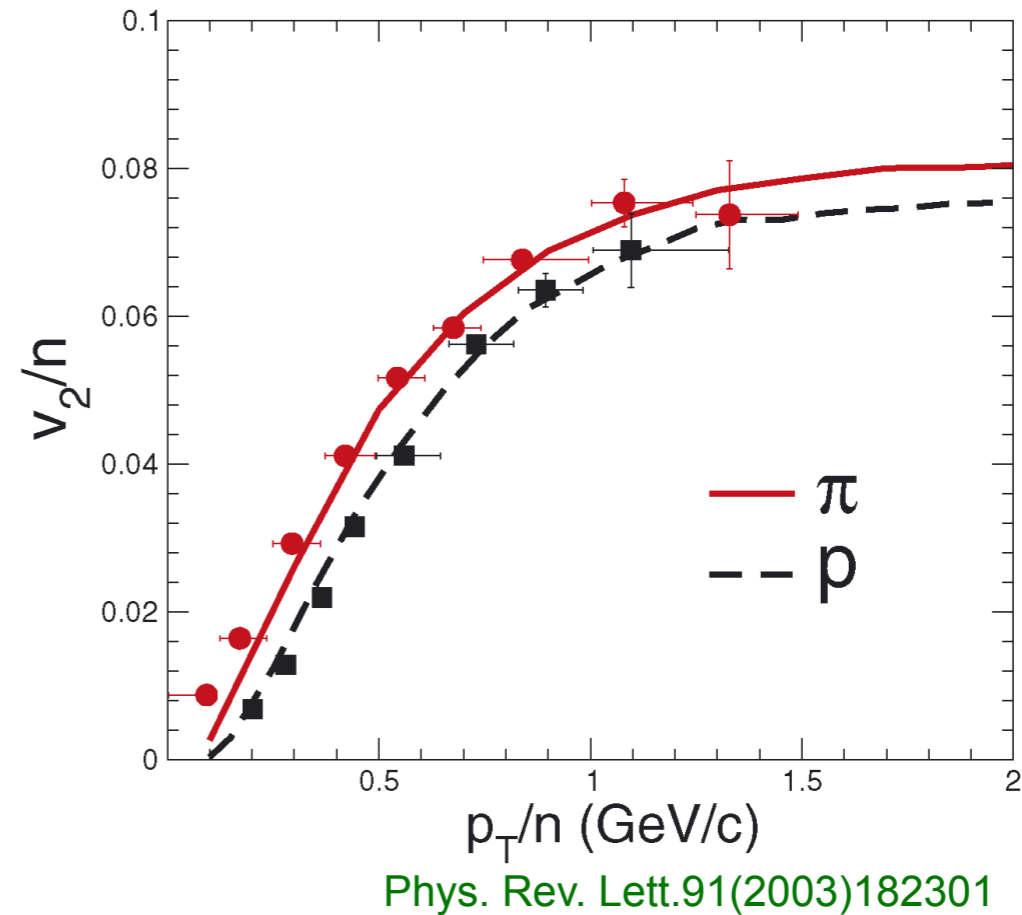
nucl-ex/0410012

Hadronization

What are the relevant degrees of freedom?



Φ meson follows π^0 trend

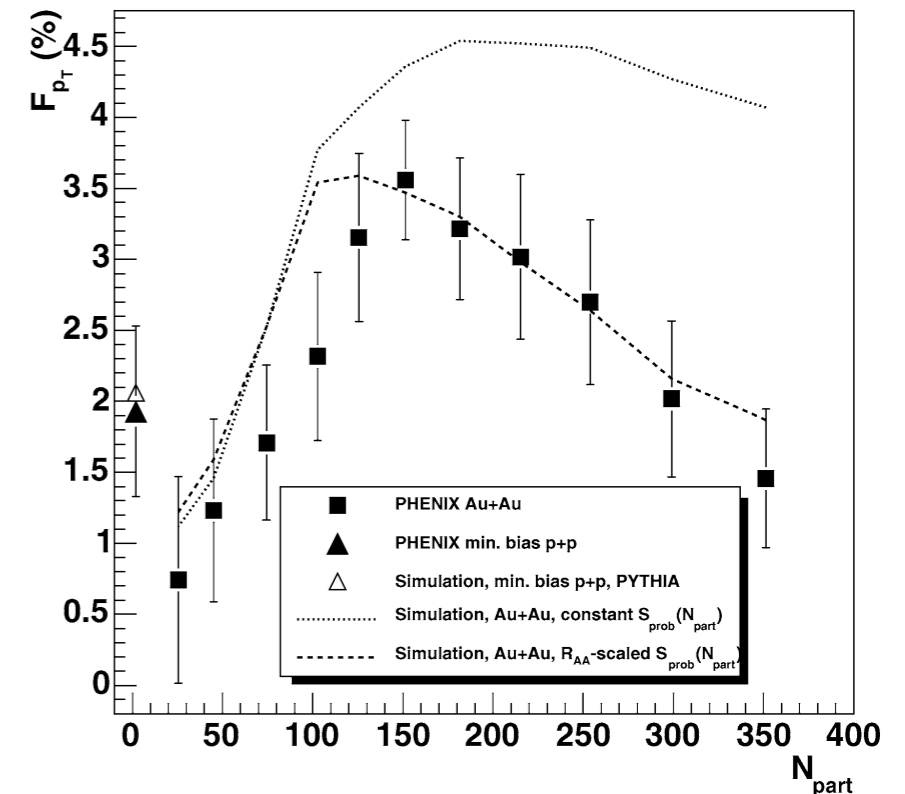
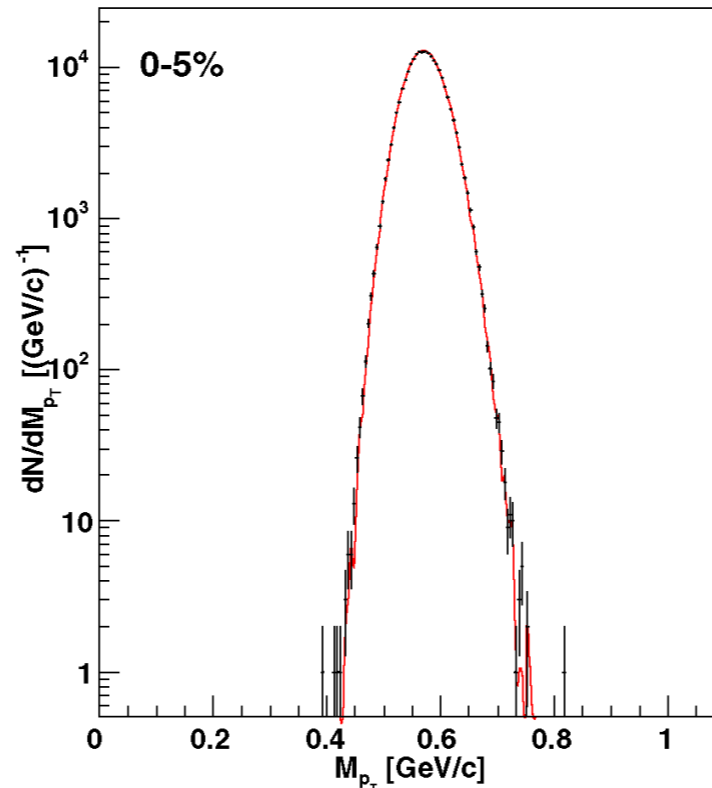
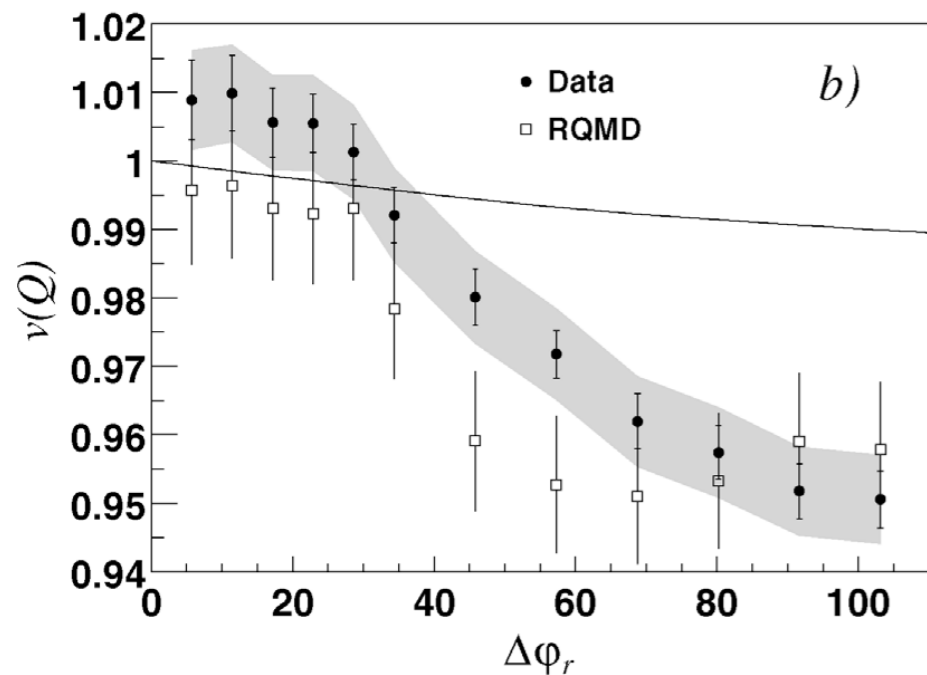


Quark Recombination models features:

- Increased Baryon Production at mid- p_T
- v_2 scales with quark number not mass

V. Greco, C.M. Ko, Phys. Rev. C70(2004)024901.

Fluctuations



$$v(Q) = \frac{\langle Q^2 \rangle - \langle Q \rangle^2}{n_{ch}}$$

$$M_{pT} = \overline{p_T} = \frac{1}{n} \sum_{i=1}^n p_{Ti}$$

$$\omega_{pT} = \frac{\sigma_{M_{pT}}}{\langle M_{pT} \rangle},$$

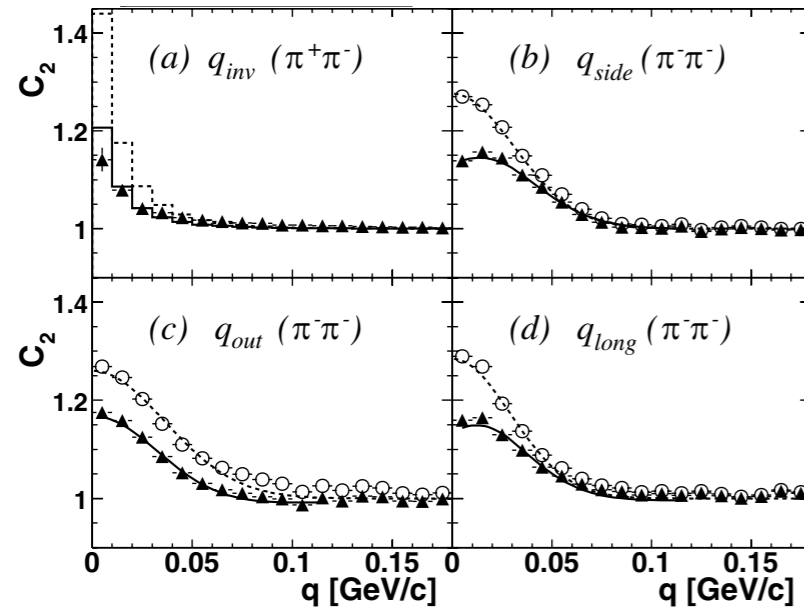
$$F_{pT} = \frac{\omega_{pT, \text{data}} - \omega_{pT, \text{mixed}}}{\omega_{pT, \text{mixed}}}$$

Non-random fluctuations in Q
associated with critical behavior near
QGP phase boundary not observed.

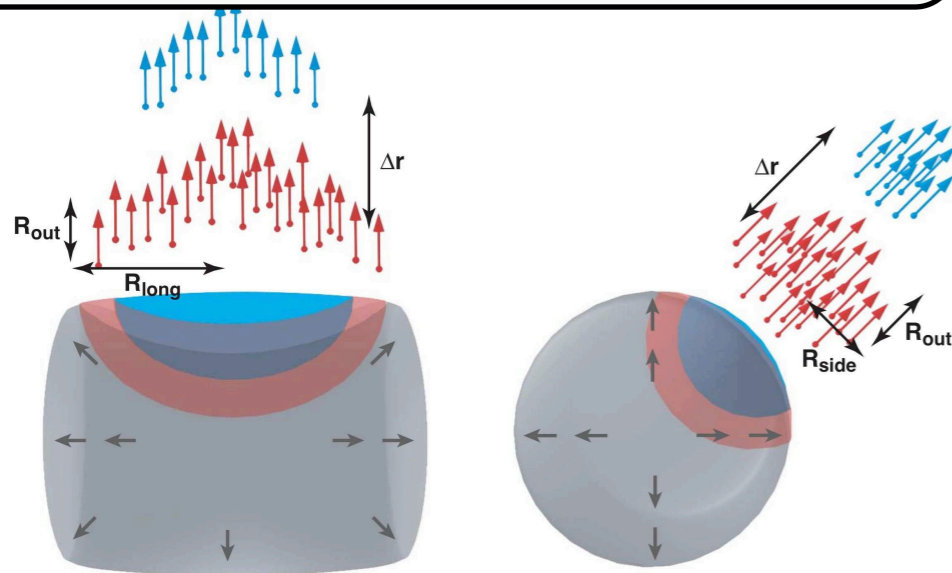
Phys. Rev. Lett. 93(2004)092301.

Femtoscopy

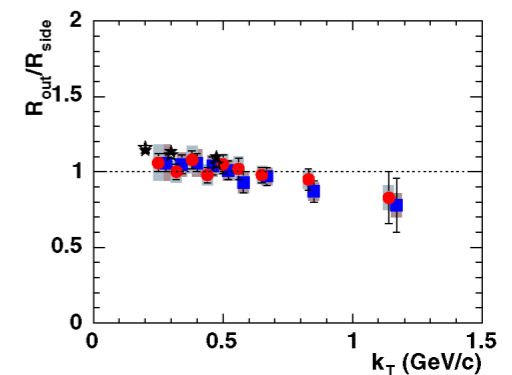
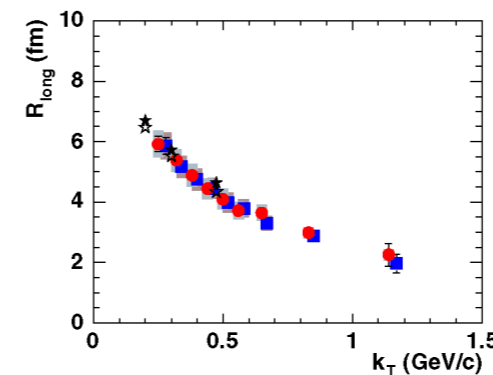
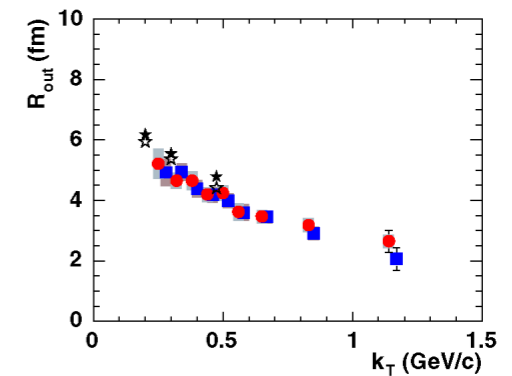
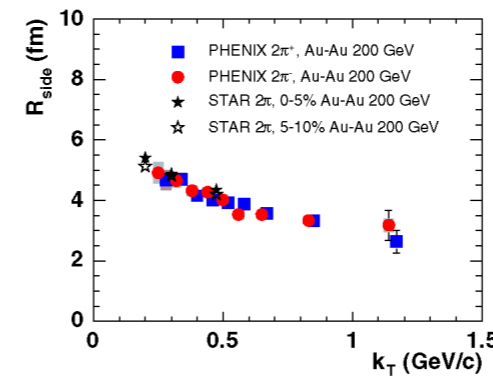
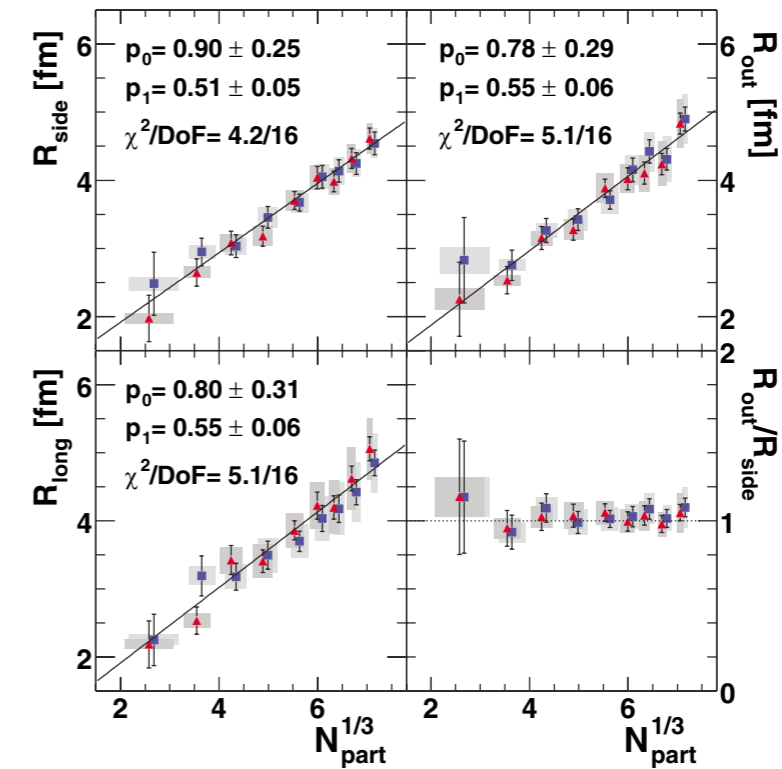
BE Enhancement at small relative momentum



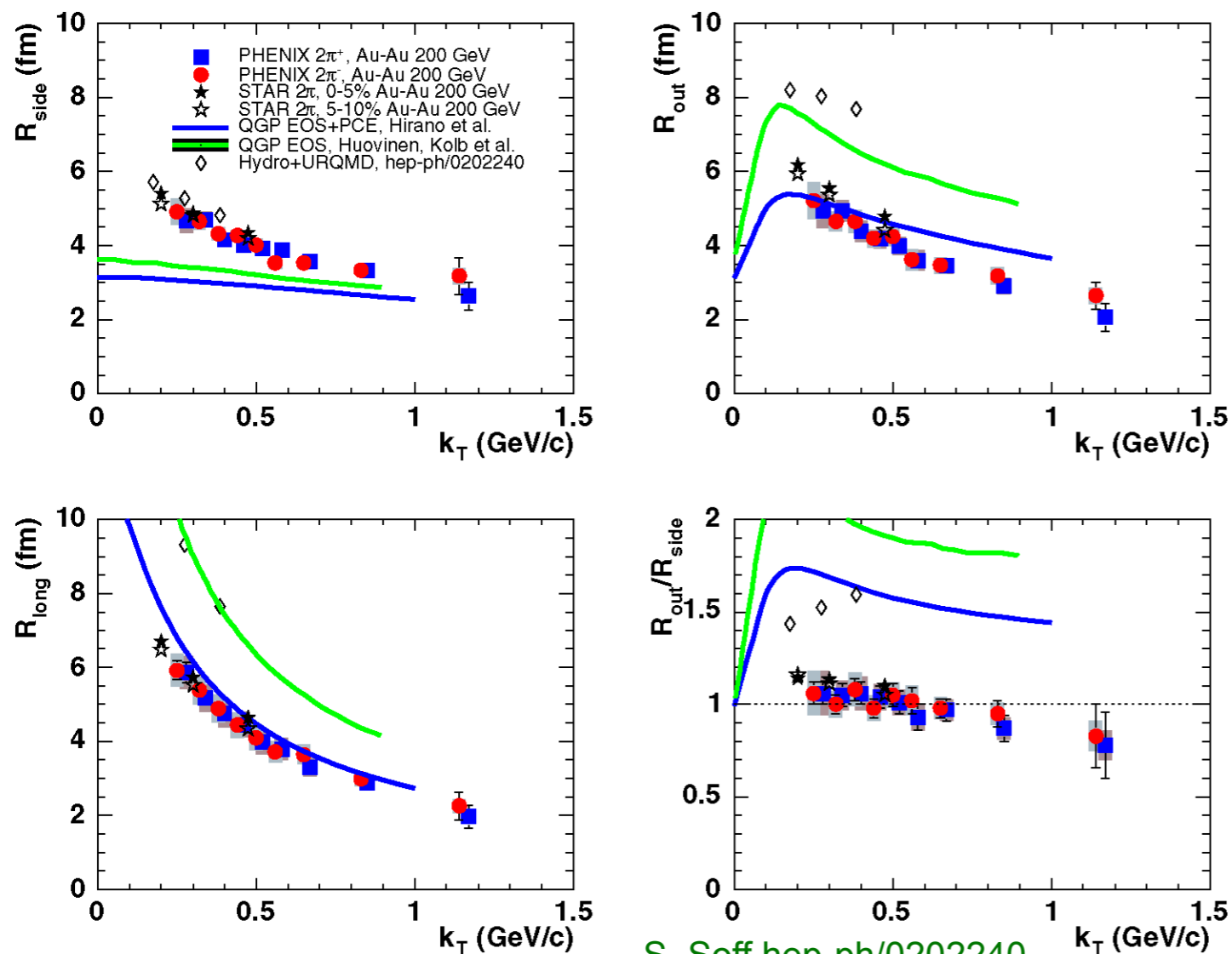
Space-Momentum Correlations



System size



HBT Puzzle



S. Soff, hep-ph/0202240

T. Hirano, K. Tsuda, Phys. Rev. C66(2002)054905

U.W. Heinz, P.F. Kolb, hep-ph/0204061

Full Hydrodynamic calculations fail to reproduce HBT radii!

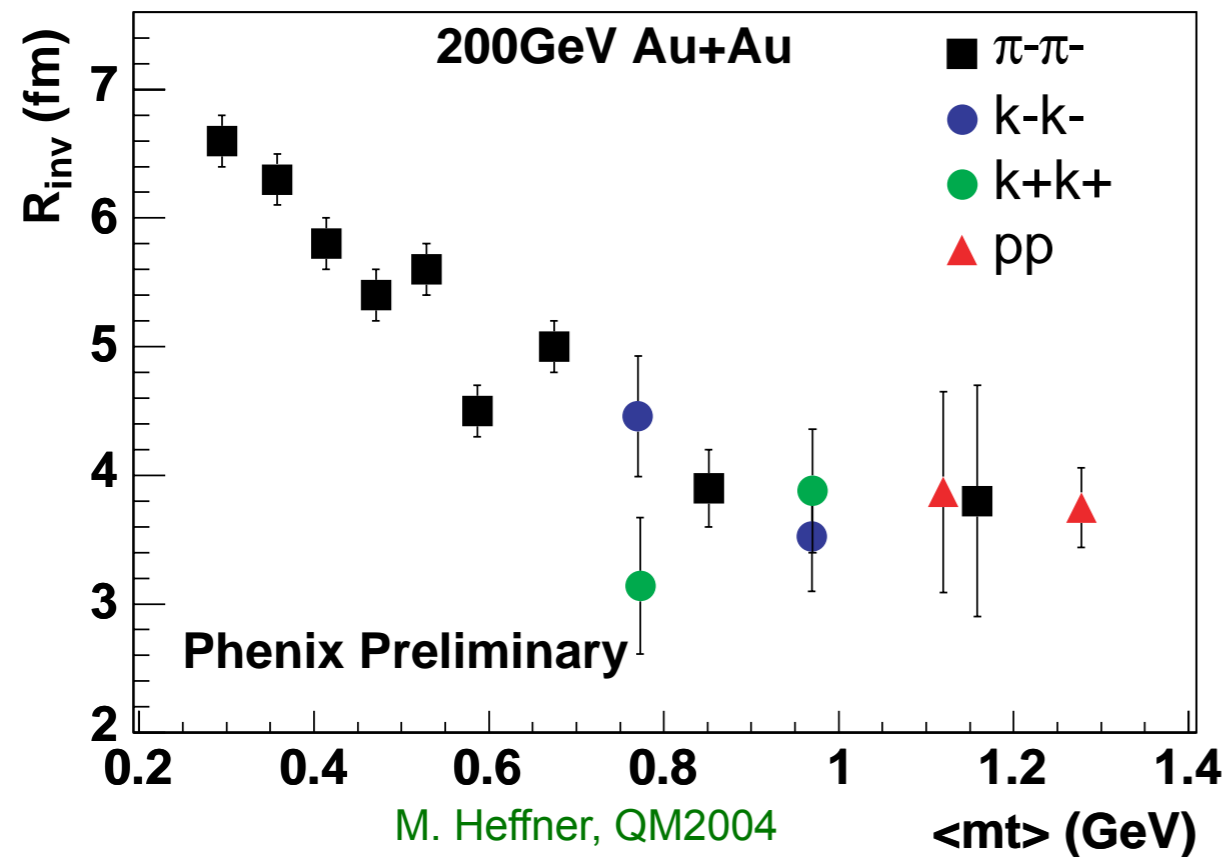
Opacity corrections?
Cramer et al.

Some Hydro Parameterizations effectively describe data:
Blast-Wave
Buda-Lund
Cracow

Future HBT analyses offer new insight

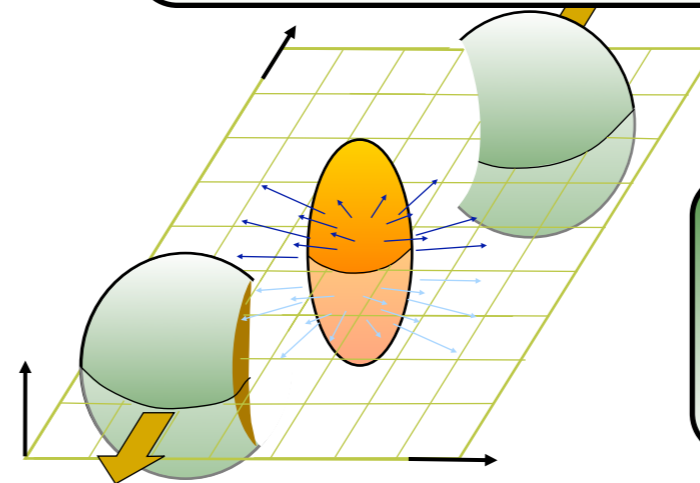
Other HBT Handles

Species Dependence



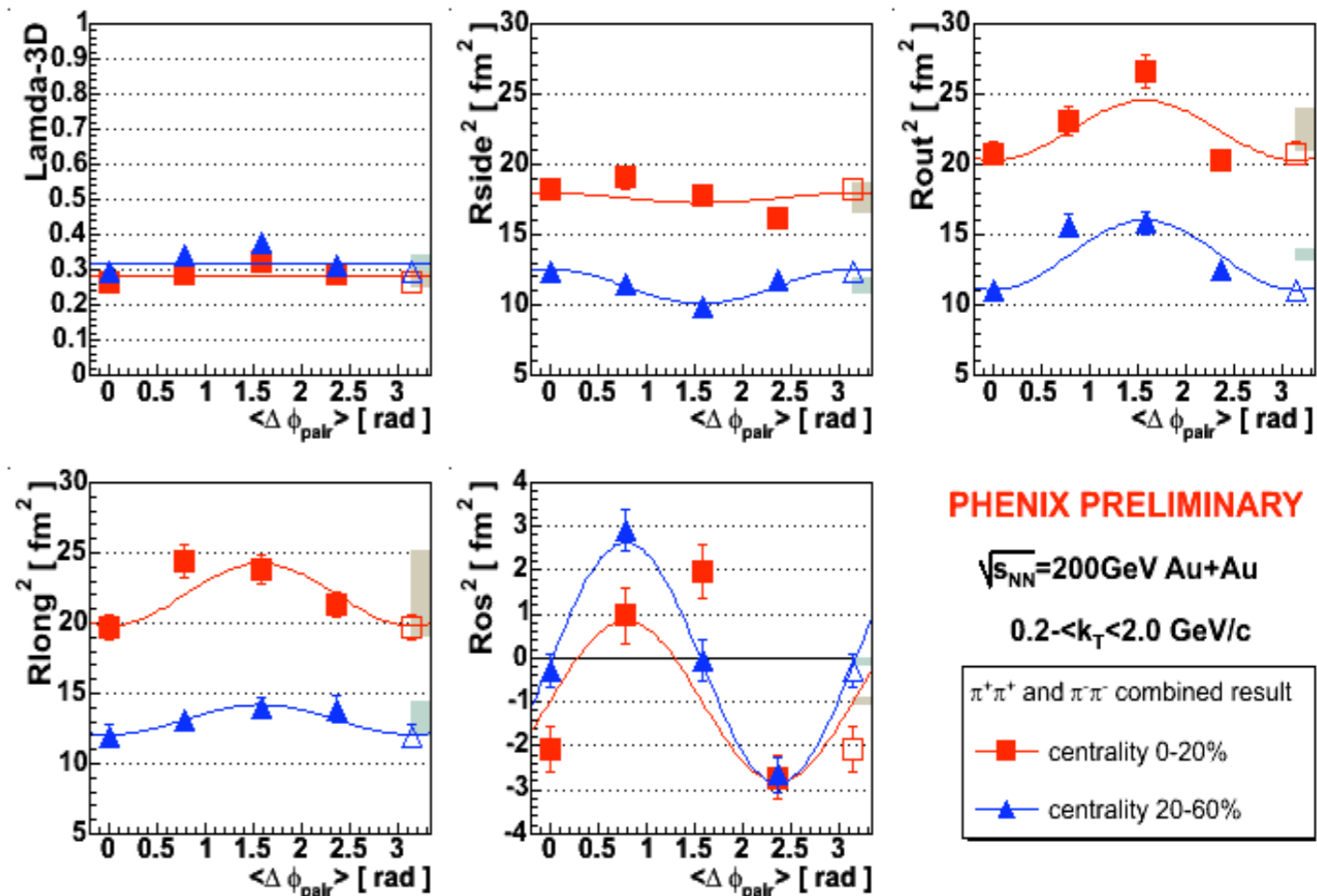
Particles in the same flow field have similar k_T dependence.

Azimuthal Dependence



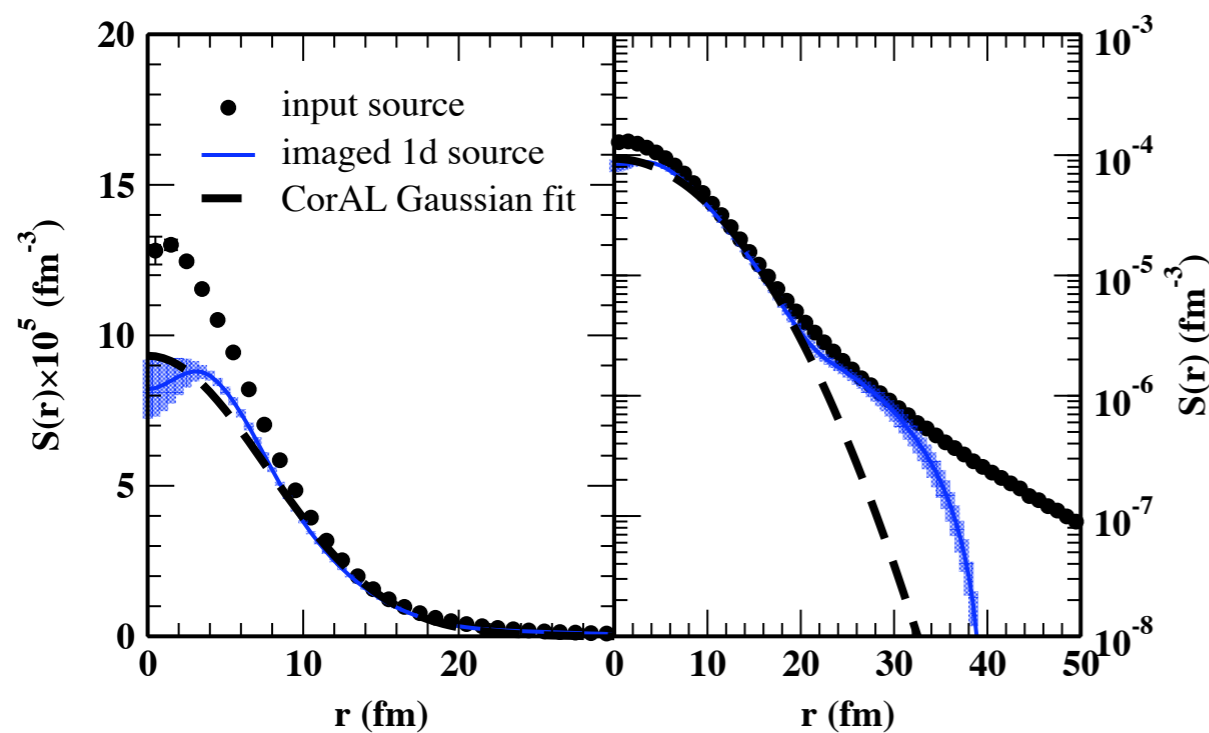
$$\epsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

T. Kawagishi, JPS-2005

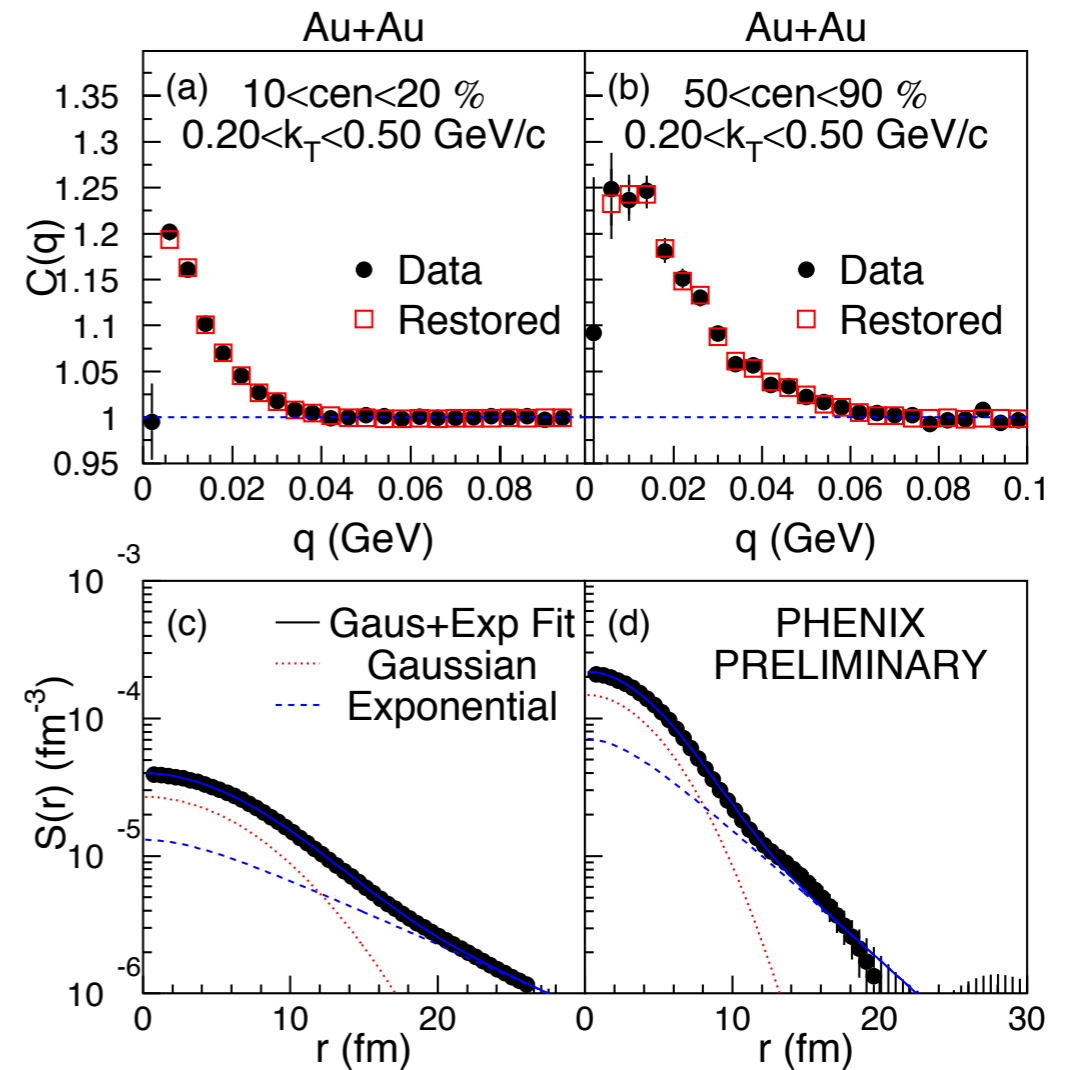


New Tools ...

HBT Imaging will
investigate non-
Gaussian Sources



nucl-th/0507015



R.Lacey, Breckenridge

Long-range structure
in the pion source.

Future Measurements

- PHENIX Measurement of Particle Yields at High p_T with Respect to Reaction Plane in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, [David Winter](#)
- High p_T p^0 , h, identified charged hadron and inclusive charged hadron spectra from PHENIX, [Maya Shimomura](#)
- Probing Cold and Hot, Dense Nuclear Media via High p_T Jets with Di-hadron and gamma-hadron Correlations with PHENIX, [Nathan Grau](#)
- Flavor Dependence of jet-correlations in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV with the PHENIX Detector, [Wolf Holzmann](#)
- Measurement of Direct Photons in $\sqrt{s_{NN}} = 200$ GeV p+p, d+Au, and Au+Au Collisions with the PHENIX Experiment at RHIC, [Stefan Bathe](#)
- Evidence for a long-range pion emission source in Au+Au Collisions at $\sqrt{s_{NN}}=200$ GeV in PHENIX, [Paul Chung](#)
- Systematic study of identified particle production in PHENIX, [Masahiro Konno](#)
- Anisotropic Flow in $\sqrt{s_{NN}} = 200$ GeV Cu+Cu and Au+Au collisions at RHIC - PHENIX, [Hiroshi Masui](#)
- Nuclear modifications and elliptic flow measurements for phi mesons at $\sqrt{s_{NN}} = 200$ GeV dAu and AuAu collisions by PHENIX, [Dipali Pal](#)
- Measurement of event-by-event fluctuations and order parameters in PHENIX, [Tomoaki Nakamura](#)
- PHENIX results on J/ ψ production in Au+Au and Cu+Cu collisions at $\sqrt{s_{NN}}=200$ GeV, [Hugo Pereira](#)
- Study of J/ ψ Production in p+p and d+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV by the PHENIX Experiment, [Sasha Lebedev](#)
- Heavy flavor production in p+p and d+Au collisions at $\sqrt{s_{NN}}=200$ GeV, from single leptons over a wide kinematic range, [Youngil Kwon](#)
- PHENIX results on Open Heavy flavor production in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, [Sergei Butsyk](#)
- Comparison of f properties as seen in dielectron and hadronic decay channels in Au+Au collisions by PHENIX at RHIC, [Sasha Kozlov](#)
- First measurement of omega-meson production with the PHENIX Experiment at RHIC, [Viktor Riabov](#)
- Measurement of low mass dielectron continuum in $\sqrt{s_{NN}}=200$ GeV Au-Au collisions in the PHENIX Experiment at RHIC, [Alberica Toia](#)
- Analysis of three-particle correlations in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at PHENIX, [Mate Csanad](#)

Summary

- PHENIX measurements of soft and hard observables are an essential component of the exciting, comprehensive physics program at RHIC.
- Multiplicity and Transverse energy measurements indicate energy densities well above QCD critical energy density, 1.5 GeV/fm^3
- Identified spectra demonstrate strong hydrodynamic flow with energy density of $\sim 5.4 \text{ GeV/fm}^3$
- Particle Ratios and identified spectra indicate thermalized medium with strangeness fully saturated
- Mid- p_T proton excess and constituent quark scaling of v_2 consistent with partonic degrees of freedom
- HBT Radii inconsistent with full hydrodynamic calculations.
- Ongoing analyses of High Statistics Au+Au and Cu+Cu datasets promise new insight.

PHENIX Collaboration

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- Saint-Petersburg State Polytechnical University, Politechnicheskayastr, 29, St. Petersburg, 195251, Russia



13 Countries; 62 Institutions; 550 Participants*

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***as of March 2005**